

Description

[STRUCTURE FOR MEASUREMENT OF CAPACITANCE OF ULTRA-THIN DIELECTRICS]

BACKGROUND OF INVENTION

[0001] Field of the Invention

[0002] The present invention generally relates to an on-chip test circuit for testing the gate oxide capacitance and more particularly to a circuit that includes a ring oscillator to allow high frequency testing.

[0003] Description of the Related Art

[0004] As integrated circuit transistors are reduced in size (e.g., scaled), gate dielectrics continue to get thinner. Gate dielectrics that have been scaled to very small values are experiencing an exponential increase in the incidence of undesirable tunneling currents, in which the gate dielectric fails to insulate the gate from the underlying substrate. In addition, the increased use of larger dielectric

DC currents requires the use of higher frequency test devices when measuring capacitance in order for the displacement current to significantly exceed the DC leakage current.

[0005] For example, in 90 nm technology, the DC leakage has reached current densities on the order of 400 A/cm^2 , requiring frequencies on the order of 100 Mhz for the displacement current to significantly exceed the DC leakage current. Ordinary test structures and test equipment are unable to perform such high-frequency measurements, making the characterization of gate oxide thickness a very difficult test, which is unable to be repeated in a manufacturing environment.

SUMMARY OF INVENTION

[0006] The invention provides an on-chip test device for testing the thickness of gate oxides in transistors. With the invention, a ring oscillator provides a ring oscillator output and an inverter receives the ring oscillator output as an input. The inverter is coupled to a gate oxide capacitor and the inverter receives different voltages as power supplies. The current drawn by the inverter provides a measurement of capacitance of the gate oxide. In a different embodiment, the invention comprises a plurality of in-

verters receiving the ring oscillator output to allow one of the terminals of a multi-terminal device to be tested. Current drawn by the inverters provides a measurement of capacitance of each of the devices under test.

[0007] The difference between the voltages supplied to the inverter is less than or equal to approximately one-third of the difference between a second set of voltages provided to the ring oscillator. Also, the difference between the voltages supplied to the inverter is less than the sum of the absolute values of the threshold voltages of the n-type and p-type FETs that make up the inverter.

[0008] The capacitance of the gate oxide is calculated by multiplying the frequency of the ring oscillator output by the difference between the voltages supplied to the inverter. The current drawn by the inverter is then divided by the result of this multiplication process. A capacitance constant for the test device is then subtracted from the result of this division process. This capacitance constant is for the test device alone, and does not include any part of the capacitance of the gate oxide capacitor. The measurement of capacitance of the gate oxide capacitor is used to determine the electrical thickness of the gate oxide through the well known relationship $T_{inv} = A \times \epsilon_{ox} / C$, where A is

the area of the gate oxide capacitor, C is the measured capacitance, and ϵ_{ox} is the dielectric constant of the gate oxide.

[0009] In method form, the invention provides a method of testing the capacitance of a device under test in an integrated circuit chip. More specifically, this method supplies the output of the ring oscillator to the inverter to produce an inverted ring oscillator output. Again, the inverter receives different voltages as power supplies. The method also inputs the inverted ring oscillator output to the device under test. The current drawn by the inverter provides a measurement of capacitance of the device under test. Again, the difference between the voltages is less than or equal to approximately one-third of the difference between a second set of voltages provided to the ring oscillator and is also less than the sum of the absolute values of the threshold voltages of the n-type and p-type FETs that make up the inverter. The capacitance of the device under test is calculated by multiplying the frequency of the ring oscillator output by the difference between the voltages supplied to the inverter. The current drawn by the inverter is then divided by the result of this multiplication process. The capacitance constant for the test de-

vice is then subtracted from the result of this division process.

[0010] Thus, the invention uses an on-chip ring oscillator to provide a high-frequency signal together with a circuit which will allow measurement of the capacitance at very high frequencies using ordinary test probes and equipment. This circuit allows full C-V (capacitance-voltage) characterization, avoiding the weaknesses associated with the use of simple ring-oscillators as a means of capacitance extractions.

BRIEF DESCRIPTION OF DRAWINGS

[0011] The invention will be better understood from the following detailed description with reference to the drawings, in which:

[0012] Figure 1 is a schematic diagram of a circuit incorporating aspects of the invention;

[0013] Figure 2 is a waveform diagram illustrating the processing achieved with the invention;

[0014] Figure 3 is a flow diagram illustrating a preferred method of the invention;

[0015] Figure 4 is a schematic diagram of a circuit incorporating aspects of the invention; and

[0016] Figure 5 is a schematic diagram of a circuit incorporating

aspects of the invention.

DETAILED DESCRIPTION

[0017] As mentioned above, the increased use of larger dielectric DC currents requires the use of higher frequency test devices when measuring capacitance in order for the displacement current to significantly exceed the DC leakage current. The invention uses an on-chip ring oscillator to provide a high-frequency signal together with a circuit which will allow measurement of the capacitance at very high frequencies using ordinary test probes and equipment. This circuit allows full C-V characterization, avoiding the weaknesses associated with the use of simple ring-oscillators as a means of capacitance extractions.

[0018] Figure 1 is a schematic diagram of one example of the invention embodied in the circuit used for on-chip high-frequency capacitance characterization. While the following embodiment is designed to find the capacitance of a device (such as an ultra-thin gate oxide), the invention can also be used to measure gate length, channel width, flat-band voltage, interconnect capacitance, etc.

[0019] The circuit shown in the example in Figure 1 includes a ring oscillator 10 and an inverter 14 comprising an P-type transistor 11, and a N-type transistor 12. The oscillator

10 is connected to a different power supply (V_{RO}) than the inverter V_{DD} . The ring oscillator 10 is capable of producing a signal of very high frequency, f , above 100 Mhz (shown in the waveform in Figure 1) with period "t". The device under test "DUT" (e.g., the capacitance of the gate oxide in this example) is shown as capacitor 14. Transistor 11 is connected to V_{DD} , while transistor 12 is connected to V_{SS} and, V_{SS} and V_{DD} can be chosen ($V_{DD} > V_{SS}$) to limit the voltage range across the DUT 14 and thus, make the capacitance measurements at a specific DC bias voltage, which is usually required for complete characterization of the DUT. Furthermore $V_{DD} - V_{SS}$ should be less than the sum of the absolute values of the threshold voltages of the n-type and p-type FETs that make up the inverter.

[0020] Figure 2 illustrates waveforms of the ring oscillator "RO" 10 (at V_{IN}) and to the DUT 14 (V_{OUT}). To measure the capacitance of the DUT 14, knowing that the current drawn in V_{DD} (or V_{SS}) is

[0021]
$$I = (V_{DD} - V_{SS}) \times f \times (C_{ckt} + C),$$

[0022] which is inverted to yield:

[0023]
$$C = I / (f \times (V_{DD} - V_{SS})) - C_{ckt}$$

[0024] where I is measured current at V_{DD} using ammeter 16, V_{DD}

and V_{SS} are the applied voltages to the circuit in Figure 1, f is the frequency supplied to V_{IN} (by the ring oscillator), and C_{ckt} represents the incidental capacitance that the test circuit itself adds to the DUT node. To separate C_{ckt} from C , the invention uses a second copy (e.g., a sample, non-testing, standards circuit) of the circuit that is not connected to a DUT to develop a constant for the capacitance of the test circuit C_{ckt} alone. Then, as shown above, the invention simply substitutes this constant for C_{ckt} in the above equation.

[0025] This is shown graphically in the waveform diagram in Figure 2. More specifically, Figure 2 shows that, at each pulse from the ring oscillator from 0 V to V_{RO} at V_{IN} , the voltage at V_{OUT} decreases from V_{DD} to V_{SS} . The capacitance of the DUT is detected from the current drawn by the inverter, I , as shown by the above equation (e.g., $I/(V_{DD} - V_{SS})$).

[0026] Thus, as shown above, the invention provides an on-chip test device for testing the thickness of gate oxides in transistors. With the invention, a ring oscillator provides a ring oscillator output and an inverter receives the ring oscillator output as an input. The inverter is coupled to a gate oxide and the inverter receives different voltages as power supplies. The current drawn by the inverter to–

gether with the frequency of the signal and the difference between the voltages provides a measurement of capacitance of the gate oxide through the relationship above. The difference between the voltages is less than or equal to approximately one-third of the difference between a second set of voltages provided to the ring oscillator in order to represent a good approximation to the differential capacitance, dQ/dV , of the DUT. Furthermore, the difference between the voltages V_{DD} and V_{SS} should also be less than the sum of the absolute values of the threshold voltages of the n-type and p-type FETs which make up the inverter in order to ensure that no short-circuit current contributes to the inverter current.

[0027] The capacitance of the gate oxide capacitor (or other device being measured) comprises the current drawn by the inverter divided by a multiplication result of the frequency of the ring oscillator output multiplied by the difference between the voltages supplied to the inverter (less the capacitance constant for the testing structure). In other words, the capacitance of the device under test is calculated by multiplying the frequency of the ring oscillator output by the difference between the voltages supplied to the inverter. The current drawn by the inverter is then di-

vided by the result of this multiplication process. The capacitance constant for the test device is then subtracted from the result of this division process. This capacitance constant is for the testing device alone, and does not include any part of the capacitance of the gate oxide capacitor. The measurement of capacitance of the gate oxide capacitor is used to determine the electrical thickness of the gate oxide.

[0028] Figure 3 illustrates the inventive method of testing the capacitance of a device under test in an integrated circuit chip. More specifically, this method supplies the output of the ring oscillator 300 to the inverter 302 to produce an inverted ring oscillator output 304. Again, the inverter receives different voltages as power supplies. The method also inputs the inverted ring oscillator output to the device under test 306. The current drawn by the inverter provides a measurement of capacitance of the device under test. Again, the difference between the voltages is less than or equal to approximately one-third of the difference between a second set of voltages provided to the ring oscillator and furthermore is less than the sum of the absolute values of the threshold voltages of the n-type and p-type FETs which make up the inverter. The capacitance of

the device under test 314 is calculated by multiplying the frequency of the ring oscillator output by the difference between the voltages supplied to the inverter (item 308). The current drawn by the inverter is then divided by the result of this multiplication process (item 310). The capacitance constant for the test device is then subtracted from the result of this division process (item 312) to produce the desired capacitance 314.

[0029] Another embodiment of this invention (shown in Figures 4 and 5) provides for similar three-terminal measurement of capacitances. In many three terminal devices 40, a capacitance network 41-43 exists among all three nodes 44-46 (A-C), represented by the schematic diagram in Fig 4. For example, it may be desirable to measure only the capacitance C_{AB} , directly between terminals A and B of Fig. 4. The invention as previously described, if applied to terminals A and B, will measure the combined capacitance of C_{AB} added to the series capacitance combination of C_{BC} and C_{AC} .

[0030] To provide for this case, a second inverter 50 is added to the measurement structure of Fig. 1, as shown in Fig. 5. This second inverter 50 receives the same power supply voltages as the first inverter 14, however the signal from

the second inverter is applied to the "third" terminal, terminal C in this example while terminal B is tied to ground. This allows the capacitance of C_{AB} (capacitor 41) to be easily determined because neither capacitor 42 (C_{AC}) nor capacitor 43 (C_{CB}) will draw power from the first inverter 14 by operation of the connections to ground and the second inverter 50. Again the average (DC) current drawn by the first inverter 14, I , is measured using ammeter 16 with V_{DD} and V_{SS} applied to the upper and lower inverter power supply terminals, respectively, and the output of the first inverter 14 applied to terminal A. As a result, the same signal voltage appears on terminals A and C, ensuring that neither capacitor 42 (C_{AC}) nor capacitor 43 (C_{CB}) will draw power from the first inverter 14. Thus, the current drawn by the first inverter 14 is used to determine the capacitance of capacitor 42. Because of this arrangement, the current drawn by one inverter provides a measurement of capacitance of one of the terminals while the remaining inverter(s) isolate the current drawn by the first inverter to only that associated with its terminal.

[0031] As in the first embodiment of this invention (shown in Figure 1), the capacitance of the device under test, C_{AB} 41, is given by $C_{AB} = (I / [f \times (V_{DD} - V_{SS})]) C_{CKT}$, where f is the

frequency of the ring oscillator, and C_{CKT} is the capacitance of the test structure alone, measured with an identical structure to that of Fig. 5 except with no device under test, and C_{CKT} is calculated by $C_{\text{CKT}} = I_{\text{ZERO}} / [f \times (V_{\text{DD}} - V_{\text{SS}})]$. I_{ZERO} is the current measured in the inverter of the test structure with no device under test.

[0032] As mentioned above, the invention can be used for a number of purposes, such as determining gate length, L_{GATE} . More specifically, gate length may be measured in the same manner, by having a few copies of the inventive circuit, each with a MOSFET of fixed channel width and varying gate length. Then, the invention compares the gate capacitance vs L_{DESIGN} (the design length of the gate of each MOSFET), which can be used to extract L_{gate} (gate length) in a well known manner. In particular, a linear relationship of L_{DESIGN} versus measured gate capacitance is established through the preceding measurements, and the correlation used to extrapolate to a value of $L_{\text{DESIGN}} = \Delta L$, where the gate capacitance is equal to just the edge (or outer fringe) capacitance of the gate. This value ΔL , gives the difference between the design length, L_{DESIGN} , and the physical gate length, L_{GATE} .

[0033] Therefore, as shown above, the invention uses an on-chip

ring oscillator to provide a high-frequency signal together with a circuit which will allow measurement of the capacitance at very high frequencies using ordinary test probes and equipment. This circuit allows full C-V characterization, avoiding the weaknesses associated with the use of simple ring-oscillators as a means of capacitance extractions.

[0034] Advantages of this invention include the ability to perform in-line manufacturing measurements of capacitances with standard equipment. This results in low test costs, short test-time, and regular monitoring of critical manufacturing processes. As a result, improved manufacturing control ultra-thin oxide processes used to fabricate ICs is possible. Thinner dielectrics with high leakage values can be reliably characterized in line, allowing for fabrication of more-advanced structures.

[0035] While the invention has been described in terms of preferred embodiments, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the appended claims.